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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3595

WEAR OF TYPICAL CARBON-BASE SLIDING SEAL MATERIALS AT TEMPERATURES TO 700° F

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SUMMARY

Wear and friction studies were made to show the effects on performance of temperature, type of mating material, and minor composition changes in typical carbon seal materials. Most data were obtained at a surface speed of 10,000 feet per minute, a load of 1000 grams on a 3/16-inch-radius specimen, and temperatures to 700° F.

Wear of carbon seal materials increased rapidly with high temperatures. The effect of temperature on wear was reduced by using chromium-plated steel as the mating surface rather than stainless or tool steel. In general, the type of carbon and impregnation of the carbon seal material had little effect on wear compared with the effect of the mating metal.

INTRODUCTION

Sliding seals have lower leakage rates (ref. 1) and therefore are replacing labyrinth seals in turbine-type aircraft engines. Low seal-leakage rates are necessary to reduce the oxidative degradation of the lubricant as well as to obtain maximum engine efficiencies. High pressure differentials, high surface speeds, and high temperatures are characteristic of operating conditions for carbon seals in aircraft turbines. Interstage compressor seals may operate with surface speeds up to 60,000 feet per minute. Shaft seals have lower surface speeds (10,000 to 30,000 ft/min) but are required to operate at higher temperatures. The shaft seals used are adjacent to bearings that in future engines may be exposed to operating temperatures to 750° F and to shutdown temperatures as high as 1000° F (ref. 2).

Advanced mechanical designs may provide future engines with more effective seals than those now in use. The seal materials, however, must be selected very carefully because the usefulness of present materials appears to be critically limited by temperature. The most

commonly used seal materials are carbon products sliding against chromium-plated steel, tool steel, or stainless steel. The carbon materials might have limited usefulness at elevated temperatures because of increased oxidation. Carbon begins to oxidize in air at 662° F (ref. 3, p. 418). Because of heat from friction, interface temperatures sufficient to cause surface oxidation of carbon materials may occur at bulk temperatures substantially lower than 662° F. Surface oxidation of carbon at the interface could cause accelerated rates of wear that would limit service life.

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The research reported herein was conducted to determine the effect of (1) temperature, (2) several conventional methods of impregnation, and (3) the mating surface material on wear and surface failure characteristics of typical carbon seal materials.

The study was conducted with friction and wear apparatus consisting basically of a loaded hemisphere of the carbon sliding against the flat surface of a rotating metal disk. Runs were made with bulk temperatures to 700° F with surface speeds of 10,000 feet per minute in an atmosphere of dried air and with no lubrication.

Acknowledgement is made to the Cleveland Graphite Bronze Company, Kuchler-Huhn Company, Ohio Carbon Company, Pure Carbon Company, Stackpole Carbon Company, Superior Carbon Company, and The United States Graphite Company for information on carbon materials and, in some cases, samples of carbons.

MATERIALS

Carbons

A list of the carbon-base materials used as rider specimens is presented in table I. Several of the materials are used for sliding seals in aircraft turbine engines. In general, the carbons of table I all have similar types of composition. They are predominantly petroleum coke but contain intermediate amounts (approx. 20 to 35 percent) of either natural or synthetic graphite (or both). They are finely milled with coal-tar pitch (binder material), molded under high pressures, and then gas baked at temperatures ranging from 1600° to 2000° F. In some cases the materials are impregnated with small amounts (approx. 5 percent) of metals, resins, pitch, inorganic salts, or organo-metallic complexes, and subsequently cured at temperatures of 350° F and higher. Impregnation serves several functions, such as, reducing porosity, increasing hardness, and increasing transverse strength; it may improve friction and wear properties as well as reduce bulk oxidation tendencies. The most common impregnants for carbons used in sliding seals of aircraft turbine engines are phenol-formaldehyde-type thermosetting resins. One

method of producing high-density, "nonimpregnated" carbons involves impregnating with coal-tar pitch (the binder) and rebaking at high temperatures.

The measureable physical characteristics of carbon materials can vary significantly with little or no detectable change in chemical properties. Production control and, therefore, significant fundamental engineering studies, of carbons are extremely difficult. Manufacturers of seals have reported difficulty in obtaining consistent results with various batches of mechanical carbons that are nominally the same. For that reason, all the data reported herein, except those obtained with material A-2, were obtained with a single batch of each material. Two batches of A-2 carbon were used to obtain the desired data; the friction and wear performance of these batches checked satisfactorily.

Mating Surfaces

The materials used for mating surfaces in these experiments included cast iron (Federal specification QQI-652), hardened M-10 tool steel (Rockwell C-62), type 347 stainless steel (Rockwell A-51), and chromium electroplated on steel.

APPARATUS AND PROCEDURE

Specimen Preparation

The rider specimens of the carbon materials investigated were cylindrical (3/8-in. diam. and 3/4-in. length) and had a hemispherical tip (3/16-in. rad.) on one end. Most carbon materials were machined in a lathe although it was necessary to grind some carbons because of extreme hardness and brittleness. No coolant was used.

The carbon rider specimens were soaked in distilled water for several hours, scrubbed with a small brush, and dried in an oven at 300° F for 2 hours. The specimens were then stored in a desiccator until used in the experiments.

The disk specimens were given a fine grind and then "superfinished" to a mirror-like surface having roughness of less than 4 rms as measured with a profilometer. The surfaces were at least as highly finished as the finest surfaces used on face-type sliding seals in turbine engines.

The disk specimens were carefully cleaned to remove all grease and other surface contamination. The cleaning procedure included scrubbing with several organic solvents, scouring with moist levigated alumina, rinsing with water, washing with ethyl alcohol, and drying in an uncontaminated atmosphere of dried air or in a desiccator.

Apparatus

Initial experiments for the purpose of correlation with face-seal wear were performed with a low surface-speed apparatus. This apparatus had a small disk specimen $\left(2\frac{1}{2}\text{-in. diam.}\right)$ operating in a cylindrical furnace (ref. 4).

A diagrammatic sketch of the apparatus used in the remainder of the experiments reported herein is shown in figure 1. This apparatus had a disk specimen (13-in. diam.) rotated by a hydraulic motor assembly that provided accurate speed control. The disk specimen was mounted on a flywheel containing resistance heaters with its shaft supported and located by a mounting block which contained bearing assemblies. These flywheel heaters are capable of providing disk surface temperatures above 700° F with surface speeds of 10,000 feet per minute.

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The atmosphere in all NACA runs had air of less than 10 percent relative humidity. Loading was accomplished by the direct application of weights through a mechanical linkage. The rider-holder assembly was mounted by flexure suspension. It was restrained through a pivot arm by a strain-gage dynamometer ring assembly that gave a direct measurement of friction force. The four strain gages on the ring were part of a Wheatstone bridge circuit that included a recording potentiometer as the strain (friction force) indicator. Friction coefficients calculated from the friction-force measurements were generally reproducible to within ±0.02

Procedure

Wear volumes were calculated from the measured diameters of wear areas obtained after the runs or from changes in the axial dimensions of the specimens. Total wear volumes were generally reproduced within 10 percent in repeated experiments.

Most data were obtained at a surface speed of 10,000 feet per minute and with a load of 1000 grams. These conditions were varied in some cases. The temperatures were measured by a thermocouple installed in the approximate center of the rider at the base of the hemisphere (3/16 in. from specimen tip). These specimen temperatures were maintained within ±10° F during the test after initial temperature stabilization.

RESULTS AND DISCUSSION

Experimental Methods

It was necessary to establish a basis for correlation of these results with experience obtained with standard seals. In a standard operating seal, factors such as the design characteristics could have important effects on wear that would overshadow the wear and surface failure properties of the combination of slider materials. Therefore, the wear studies reported herein were made with a simple specimen configuration that would eliminate design and fabrication variables; namely, a hemisphere of carbon sliding on the flat surface of a rotating metal disk.

Data were made available by the Pure Carbon Company showing wear trends for seals made from several of their commercial grades of carbon. One series of wear data on a typical phenol resin impregnated carbon run against cast iron at various temperatures is shown in figure 2(a). The specimens consisted of an annular carbon ring running with the flat face (1-in. outside diam.) against a polished cast iron surface. The surface speed was low (426 ft/min) but the unit loading (20 lb/sq in.) was about the maximum presently used in design of aircraft turbine-engine seals.

A series of data similar to figure 2(a) is presented in figure 2(b) obtained with a hemisphere of the same type of carbon sliding against a cast iron disk. The cast iron disk had essentially the same chemical and physical characteristics as the cast iron used by the Pure Carbon Company. The data of figure 2(b) were obtained with a small $\left(2\frac{1}{2}\text{-in. diam.}\right)$ disk at a surface speed of 400 feet per minute and with 1000 grams load on the hemispherical specimen.

Comparison of figures 2(a) and (b) shows that the wear trends are similar. An abrupt increase in the slope of the wear-temperature curves occurred in both cases when the temperature was approximately 225° to 250° F. In spite of the fact that experimental procedures were quite different, similar trend correlations were also obtained with other carbon seal materials. The marked effect of temperature on wear would appear to be a critical factor from both types of experiment.

Type of loading in these experiments may be considered by some designers as an invalidating departure from seal design practice. Unit loading is considered an important criterion in seal design. The data of figure 3 show that the rate of wear (slope of curve) was not affected by changing unit loads (from more than 173 to 41 lb/sq in.) as the wear area became larger during the $29\frac{1}{2}$-hour run. The open symbols denote wear on the 3/16-inch-radius tip of the rider when unit loading was changing as a result of wear. The filled symbols represent data for

the cylindrical sections when unit loading was not changing with wear. The test specimen with the smaller-diameter cylindrical section (more than twice the unit loading) had essentially the same wear rate as the specimen with the larger-diameter cylindrical section.

The effect of total load on wear rates for carbon using cylindrical specimens of different diameters is presented in figure 4. Each data point in figure 4 represents a wear rate determined in separate runs of from 3- to 5-hour duration. These runs were made after the radiused tips of the specimens had been worn away. Wear volume increased linearly with increased total load, but unit loading had no independent effect on wear volume. This can be seen from data of figure 4 at constant total load but with different unit loads. For example, at 1000 grams total load, the unit loads were 41, 100, and 200 pounds per square inch for the specimens with different diameters, and the respective wear volumes were 0.059×10^{-3}, 0.058×10^{-3}, and 0.054×10^{-3} cubic inches per hour. 3921

Results previously obtained with small load areas and metal specimens also indicated that total load was more important than unit load. In tests with a hemispherical specimen under constant total load (where wear caused a continual decrease in unit loading), the volume of material worn away per unit time was approximately constant in most cases (ref. 5). Departures from a constant wear rate could usually be explained on the basis of such factors as the formation of surface films.

The advantages of using a hemispherical specimen are that (1) a very accurate measure of wear volume can be obtained, (2) the influence of nonparallelism of surfaces as well as elastic and thermal distortion in the apparatus can be minimized, and (3) contact conditions can be defined. Preliminary investigation with flat carbon specimens in the friction apparatus demonstrated that friction force was sufficient to cause misalinement and produce edge loading. This condition occurred even when surfaces were lapped to within three light bands of flatness prior to running. In fact, the nominal unit loads were misnomers until the surfaces were worn to full face contact.

The effect of total load on wear of hemispherical carbon specimens sliding against type 347 stainless steel is shown in figure 5. The runs were made with a carbon-specimen temperature of 500° F and with a sliding velocity of 10,000 feet per minute. A linear effect of total load on wear is shown for all except the maximum load. The high wear at the greatest load may have been caused by inadequate mechanical strength rather than by fundamental wear properties. The temperature condition was such that surface spalling of the carbon specimens occurred; which may be the reason the curve in figure 5 does not go through the origin. Subsequent experiments were run at a load (1000 g) high enough to give rapid wear but low enough to prevent mechanical failure of the carbon materials.

Temperature and Mating Material

The effect of temperatures up to 700° F on wear of the carbon specimens is shown in figure 6. These runs were made with hemispherical specimens of a typical carbon impregnated with phenol resin sliding against disk specimens of various metals.

High hardness value has been one of the primary guides used by designers in selecting mating materials to be run against mechanical carbon. Comparison of results of a very hard M-10 tool steel (Rockwell C-62) with the results of a relatively soft type 347 stainless steel (Rockwell A-51) indicated that other factors were more important. At temperatures lower than 400° F wear was approximately the same for both metals. Wear of carbon specimens began to increase rapidly with both metals when temperatures were sufficiently high to cause visible interference coloration by oxidation of the metal.

Wear of the carbon was significantly lower at all temperatures when runs were made with chromium-plated disks. The chromium-plated steel had greater hardness and better resistance to oxidation than either the tool steel or the 347 stainless steel. At the highest temperature, however, the chromium-plated steel oxidized and exhibited a tendency for wear increase with temperature increase. The factors contributing to wear at high temperatures are discussed in the following paragraphs.

Increase in wear of carbon materials should be expected when they are run in air at temperatures around 700° F regardless of the mating surfaces. Carbon begins to oxidize in air at 662° F to produce carbon dioxide or carbon monoxide (ref. 3). Thus, direct oxidation could be partly responsible for accelerated wear at high temperatures. Oxidation of carbon may also be part of the wear phenomena at bulk temperatures much lower than 662° F. Friction heat would cause interface temperatures exceeding 662° F at bulk carbon temperatures that are considerably lower. Furthermore, because the heat flow path in these experiments is from the flywheel heaters, through the disk, and then to the carbon specimen, the bulk material temperature at the region of contack would be higher than the value measured in the carbon 3/16 inch from the contacting interface (heat source).

At high temperatures, carbon is a chemically active material (ref. 3, p. 417). Friction heat can cause surface temperatures approaching the melting point of one of the materials in contact (ref. 6). With carbon sliding on steel, chromium, or other metals, temperatures of 2000° F or higher appear likely at the contacting asperities. The possibility of chemical reaction between carbon and the mating metal (via its oxide film) must then be considered. Chemical reaction of the carbon with the mating surface would directly consume the carbon and thereby contribute to total wear. Possibly more important is the

strength of the chemical bond forces between reacting materials. These forces might produce adherence of carbon particles to the mating surface sufficient to overcome the strength of the binder (coal-tar pitch). The result could be mass "pull-out" of carbon particles. This factor may contribute to the spalling or "cropping" of material from running surfaces of carbon seals. Figure 7 shows a typical spalled surface compared with the normal running surface of typical mechanical carbon specimens.

In the experiments with the tool steel, considerable spalling from the carbon surfaces was noted at temperatures of 400° F and higher, and the severity of the spalling increased with the higher temperatures (fig. 6). However, the amount of spalling was significantly less with the 347 stainless steel. With chromium-plated steel it was difficult to detect any spalling with a microscope, even after runs at 700° F.

The chemical processes at the interface with carbon sliding against metals may involve (1) direct oxidation of the carbon by the atmosphere, (2) reduction of the metallic oxides, and (3) formation of metallic carbides. This suggests that the wear of carbons may be reduced by providing mating surfaces that are resistant to chemical reactions. One approach would be to use a metal requiring the maximum heats of reaction to reduce the oxide and form a carbide. Another approach would be to run the carbon material against a carbide surface where no further reaction is likely to occur (except with the bonding medium of the carbide).

Type of Carbon

The wear properties of five different base grades of carbon, with and without phenol formaldehyde resin impregnation, were determined at 500° F. Runs were made against both 347 stainless steel and chromium-plated steel. Three of the materials, two impregnated grades and one not impregnated, are used in the manufacture of sliding seals for aircraft turbines. Two of the grades were cured at the special high temperature of 600° F. The usual cure for phenol formaldehyde resin impregnants involves temperatures from 350° to 400° F.

Considerable difference in wear of different base grades of carbon run against 347 stainless steel is shown in figure 8(a). With two materials the presence of the impregnant caused significant reduction in wear against stainless steel. The high-temperature cure (600° F) of the resin gave wear similar to that of the standard-cure (350° to 400° F) material.

The effect of both the type of carbon and the phenol resin impregnant on total wear was less with chromium-plated steel than with type 347 stainless steel. Similar base grades of carbon can give

widely varied wear results (fig. 8(a)). The total effect of carbon grade on wear was reduced by running with chromium-plated steel. With chromium-plated steel, impregnation gave slightly increased wear rather than the expected wear reduction. It was observed that, in general, the phenol resin impregnation did reduce friction. Friction of phenol resin impregnated grades was more erratic with the base carbon of low porosity.

One of the problems reported with seals in turbine-type engines is 3921 the formation of resinous films on the mating metal surface. In some cases the resinous films are reported to have occurred with no lubricant present; in others (ref. 7) it was definitely formed by coking the lubricant. In these experiments carbons impregnated by phenol resin were the only materials that produced resinous films on the mating metal surface. High-temperature cures seemed to reduce the tendency for resin film formation. However, the resin film obtained with carbons having phenol resin impregnation was not considered objectionable.

Comparative friction data for graphite and amorphous carbon materials are reported in reference 8 (p. 452). The types of carbon discussed herein are mixtures of carbon (high percentage) and graphite CL-2 (low percentage). Because graphite has a higher oxidation temperature and also gives lower friction (ref. 8) than amorphous carbon, materials with high graphite content should be considered for high-temperature seals, even though graphite is mechanically weaker than amorphous carbon.

Type of Impregnation

The effect of the type of impregnation on wear was studied by using a standard base material (A of table I) with fairly high porosity and with various types of impregnation. The impregnants included a phenol formaldehyde resin, silver, a metallic haloid, and an organometallic complex. Data from figures 9 and 10 show runs for both 347 stainless steel and chromium-plated steel with no heat added and with a carbon-specimen temperature of 500° F.

With the type of impregnation reported herein, wear was several times greater at 500° F than when no heat was added (figs. 9 and 10). Impregnation had little effect on wear compared with the effect of the mating materials.

In these runs the effect of the phenol resin impregnant on friction was less pronounced than in runs with lower porosity-base carbons. The minimum friction coefficient was higher with the more porous material; however, the friction was much more stable.

The metal haloid impregnation resulted in higher friction than any other material with the same base grade of carbon. However, from the standpoint of wear reduction the haloid appears to be the most effective of the impregnants (figs. 9 and 10). The haloid formed an extremely thick (several thousandths in.) film on mating surfaces. This film might interfere with operating tolerances in some mechanisms. Also, high friction indicated that the film material had high shear strength. The undesirable influence of the haloid on friction was further demonstrated by the normal running temperatures against 347 stainless steel when no heat was added. The temperature of the specimen during the run was around 250° F whereas most similar materials operated at temperatures at least 100° F cooler.

Silver impregnation gave slightly less wear and friction than the base carbon at 500° F. Minute silver particles were transferred to the mating surface but appeared to have no adverse effect on friction and wear. The silver may have masked bulk oxidation of the carbon at the interface. Silver appeared to flow over portions of the contacting surface of the carbon specimens.

The organo-metallic complex was intended primarily as an oxidation inhibitor. Wear tracks on the metal surfaces appeared similar to those obtained with nonimpregnated carbons although there was a slight tendency for film formation indicated by surface discoloration. This impregnant had little effect when run against 347 stainless steel; it was somewhat effective against chromium-plated steel at 500° F.

Impregnation of carbon to reduce oxidation, as well as for film formation, would appear to be a sound concept. Both silver and the organo-metallic complex may have functioned in this manner.

SUMMARY OF RESULTS

A series of wear and friction experiments with carbon seal materials sliding against various metals gave the following results:

1. Wear of carbon materials was accelerated rapidly by operation at high-temperature levels. Increased wear appeared related to the formation of visible oxide films on the mating metal surface.

2. The adverse effect of temperature on wear of carbon was minimized by use of chromium-plated steel as the mating surface. Chromium-plated steel gave less wear than type 347 stainless steel. At temperatures above 400° F, M-10 tool steel gave more wear than type 347 stainless steel.

3. In some cases impregnants were effective in reducing wear. The relative effectiveness of impregnants changed with varied mating materials and at different temperatures. Chromium-plated steel gave less wear with all types of impregnated carbon then did type 347 stainless steel.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, December 1, 1955

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TABLE I. - TYPICAL PROPERTIES OF GAS-BAKED CARBON-BASE MATERIALS

[Data from manufacturers.]

Material (a)	Type of impregnation	Maximum cure temperature, °F	Porosity, percent (approx.)	Average hardness (b)	Transverse strength, psi
A-1	None	---	11.5	80-95	9,000 min.
A-2	Phenol resin	350	5.6	80-100	11,000
A-3	Silver	---	5.8	80-95	15,000
A-4	Metal haloid	---	4.9	85-95	10,000
A-5	Organo-metallic complex	---	6.0	------	------
B-1	None	---	5	75	10,000
B-2	Phenol resin	400	.1	95	12,000
B-3	Phenol resin	600	.1	95	12,000
C-1	None	---	5	70	9,000
C-2	Phenol resin	400	.2	80	10,000
C-3	Phenol resin	600	.2	80	10,000
D-1	None	---	---	75	6,000
D-2	Organic resin	400	---	75	6,000
E-1	None	---	5	80	9,000

[a] All material numbers having the same letter prefix are for grades of carbon made from the same base grade. Differences within letter groups result from various impregnants and curing temperatures after impregnation.

[b] Scleroscope

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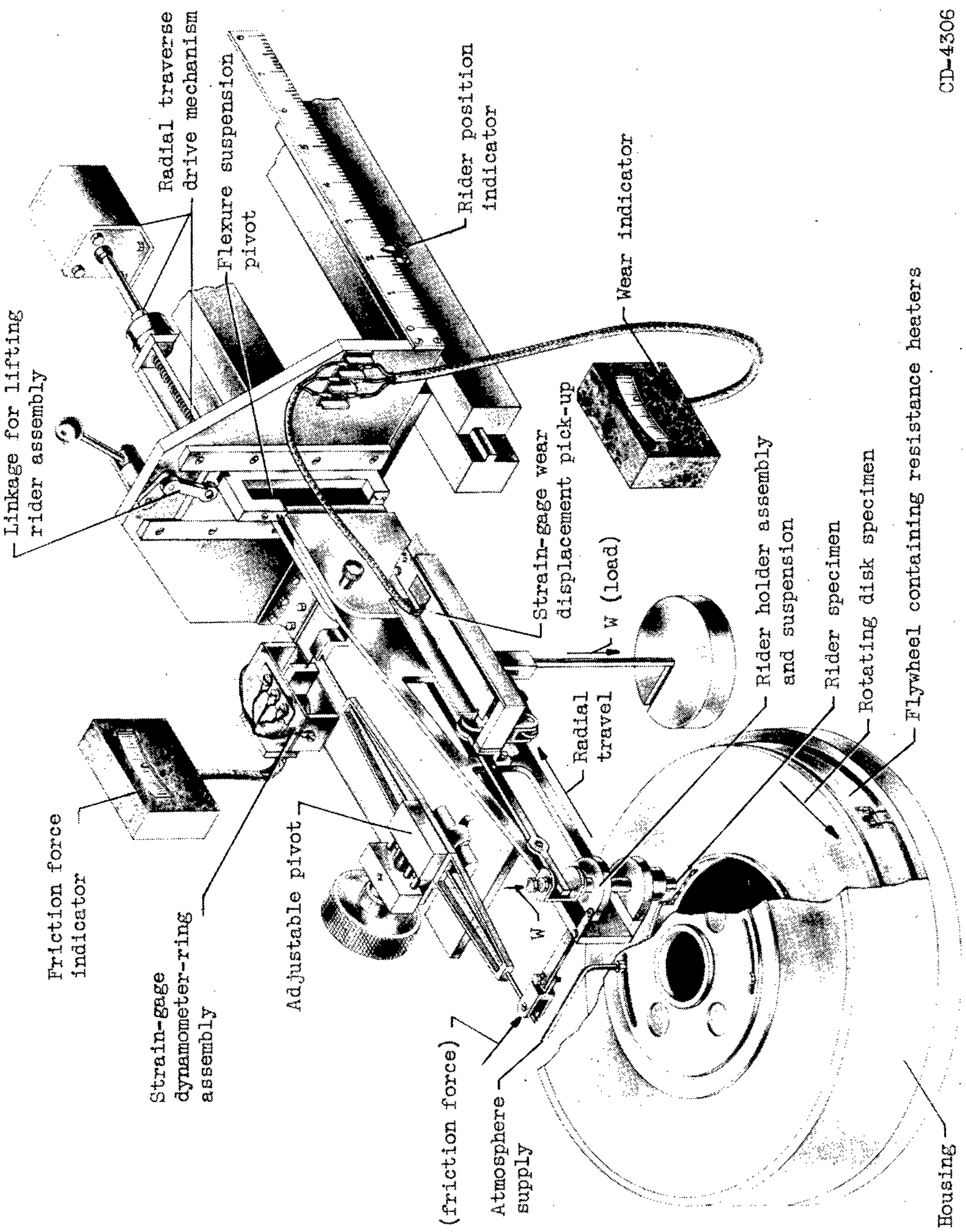

Figure 1. - High-temperature and high-sliding-velocity friction apparatus.

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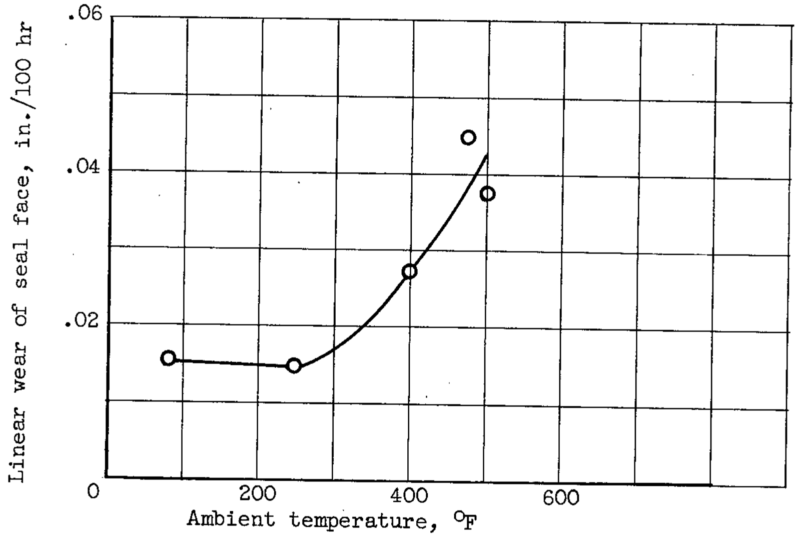
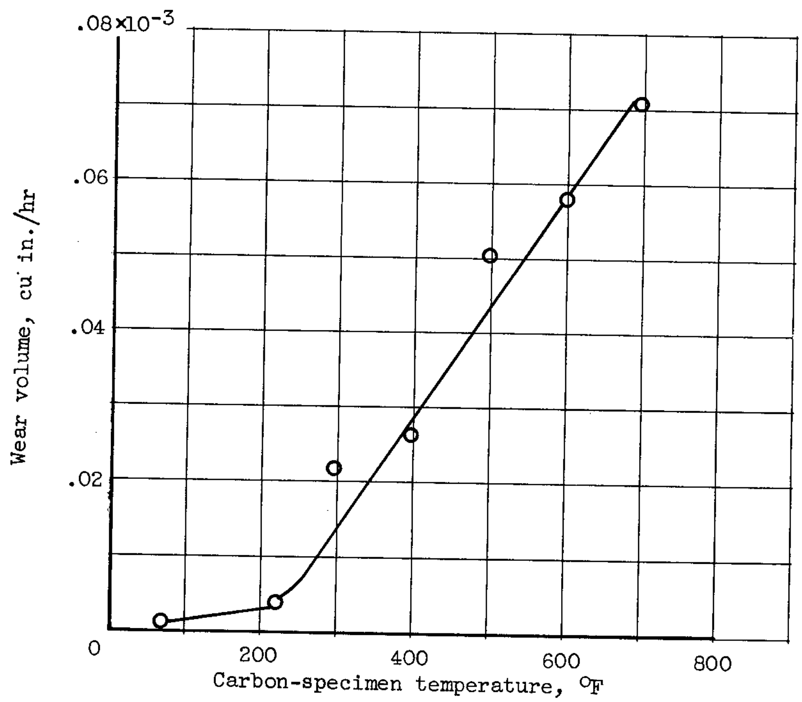


(a) Annular face seal specimen. Ring outside diameter, 1 inch; unit loading, 20 pounds per square inch; surface speed, 426 feet per minute; no control of atmosphere. (Data from Pure Carbon Company.)



(b) Hemispherical tip specimen. Radius of tip, 3/16 inch; load, 1000 grams; surface speed, 400 feet per minute; atmosphere, dry air.

Figure 2. - Effect of temperature on wear of a typical phenol resin impregnated carbon seal material sliding on cast iron.

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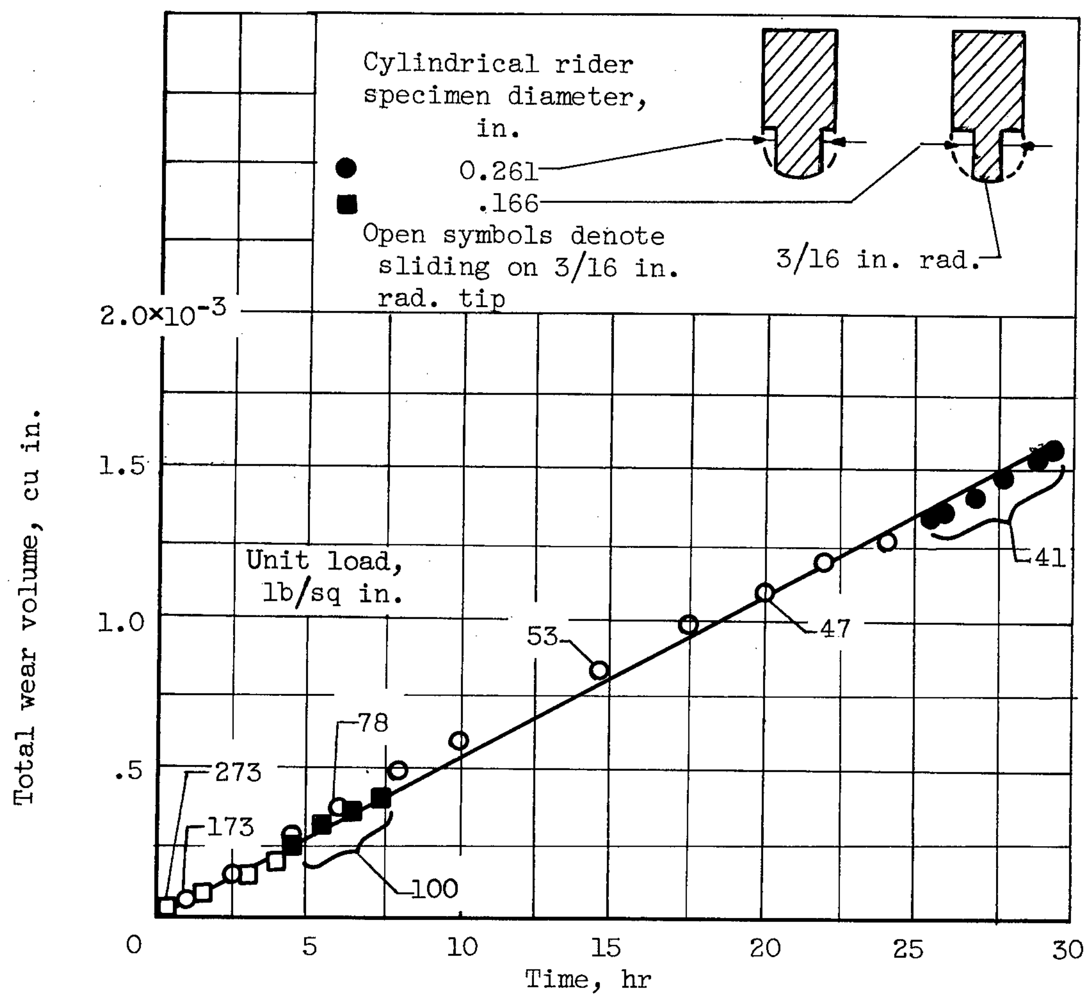


Figure 3. - Effect of running time on total wear volume of typical carbon seal material sliding on chromium-plated steel. Load, 1000 grams; carbon-specimen temperature, 360° F; surface speed, 10,000 feet per minute; atmosphere, dry air.

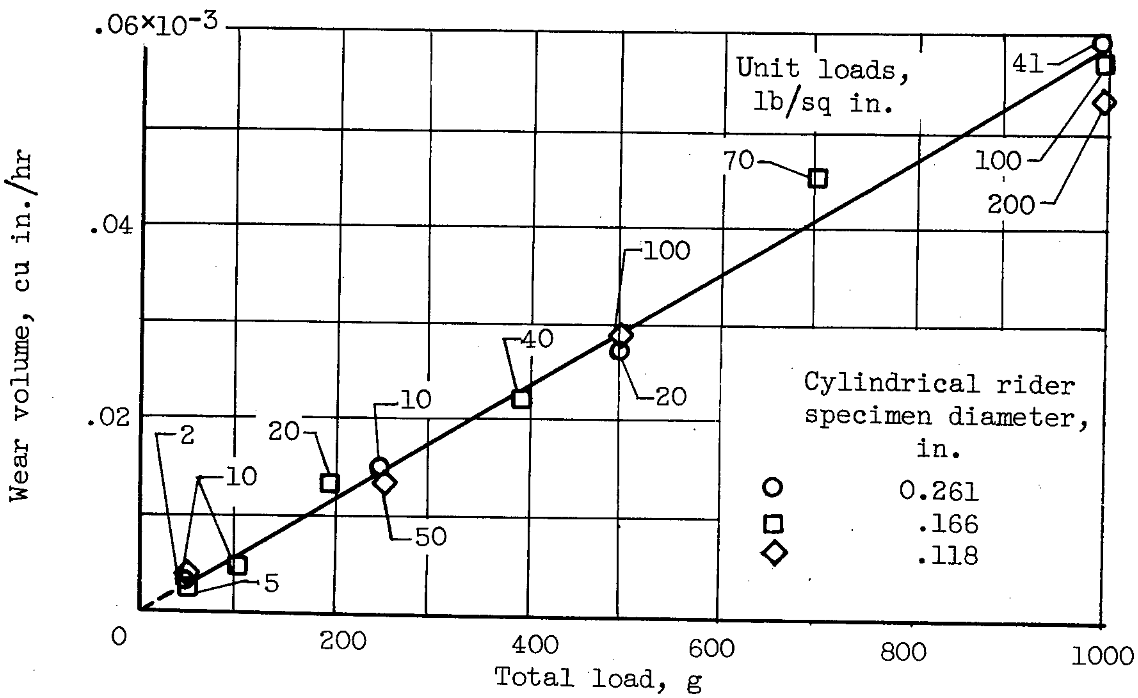


Figure 4. - Effect of total load on wear volume of typical carbon seal material sliding on chromium-plated steel. Carbon-specimen temperature, 360° F; surface speed, 10,000 feet per minute; atmosphere, dry air.

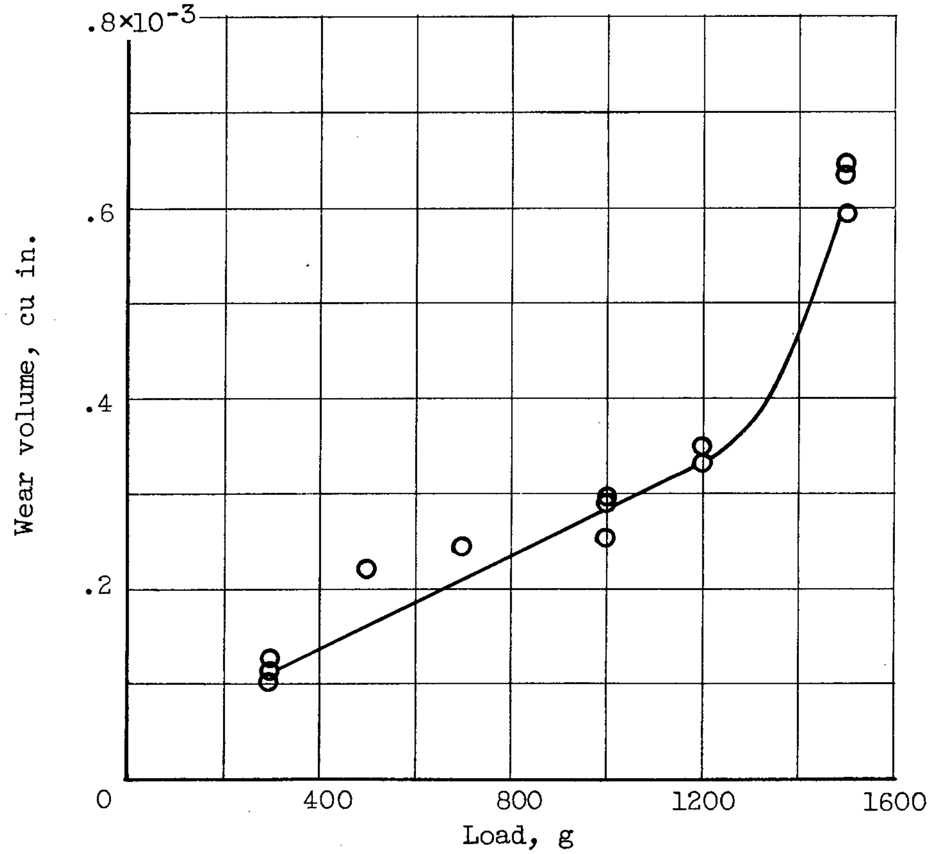


Figure 5. - Effect of load on wear of typical phenol resin impregnated carbon seal material sliding on 347 stainless steel. Carbon-specimen temperature, 500° F; surface speed, 10,000 feet per minute; atmosphere, dry air; duration, 1 hour.

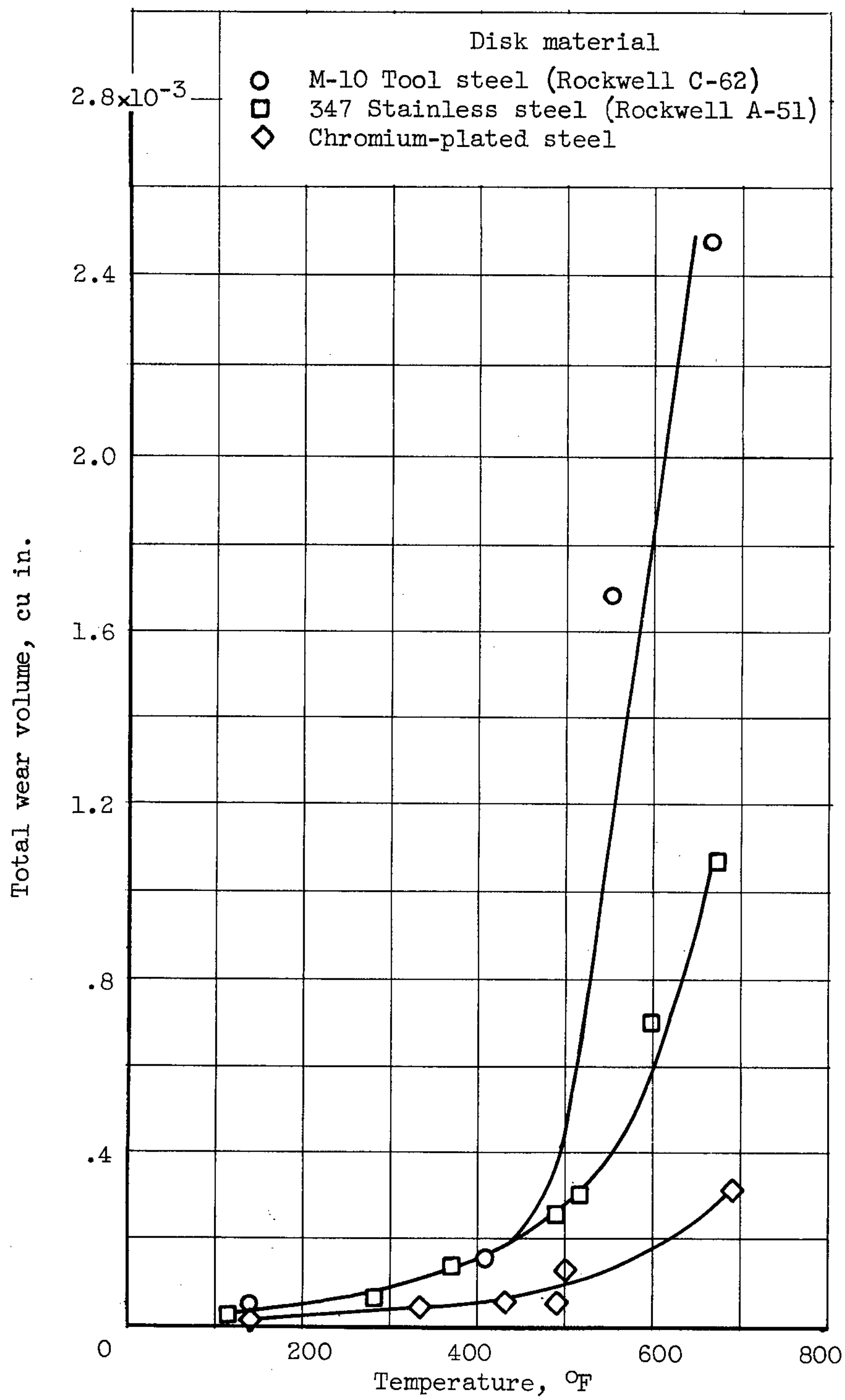
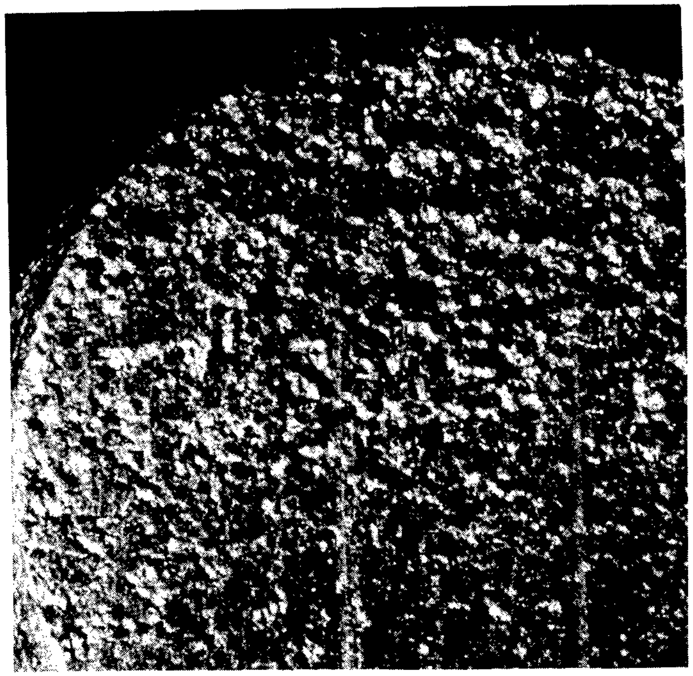
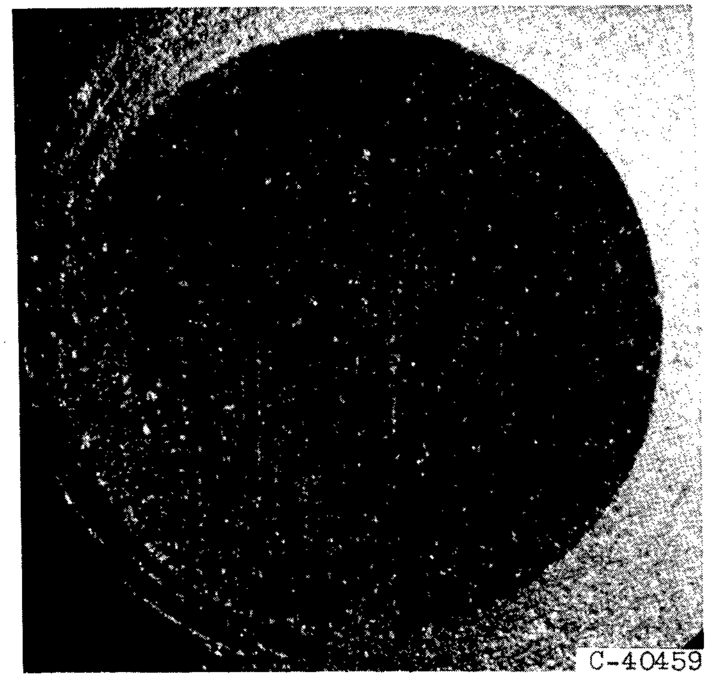


Figure 6. - Effect of temperature on wear of typical phenol resin impregnated carbon seal material run against various materials. Load, 1000 grams; surface speed, 10,000 feet per minute; atmosphere, dry air; duration, 1 hour.

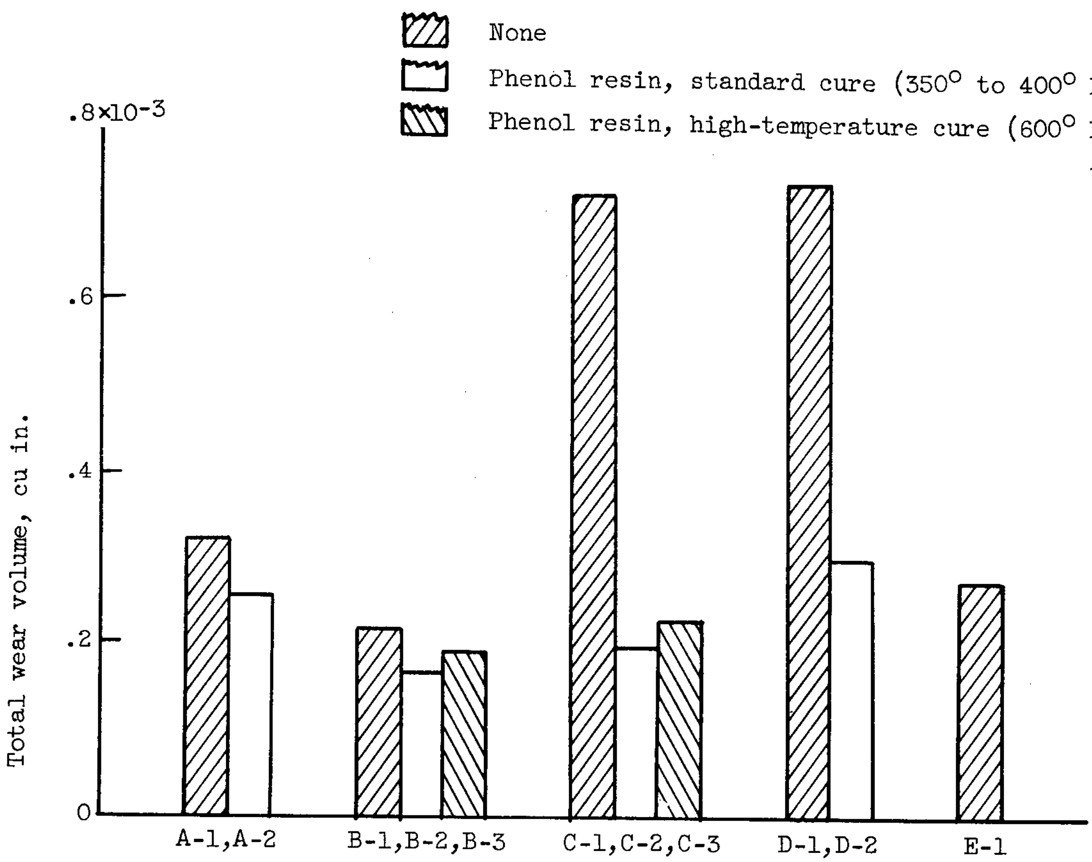


(a) Spalling.

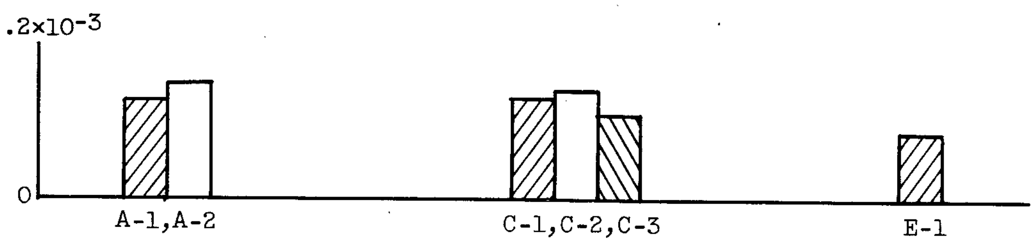


(b) Normal wear.

Figure 7. - Photomicrographs of worn surfaces of typical carbon seal specimens after wear and friction experiments. X15



(a) 347 Stainless steel disk.



(b) Chromium-plated steel disk.

Figure 8. - Wear of typical carbon seal materials with and without phenol resin impregnation run against 347 stainless steel and chromium-plated steel. Carbon-specimen temperature, 500° F; load, 1000 grams; surface speed, 10,000 feet per minute; duration, 1 hour.

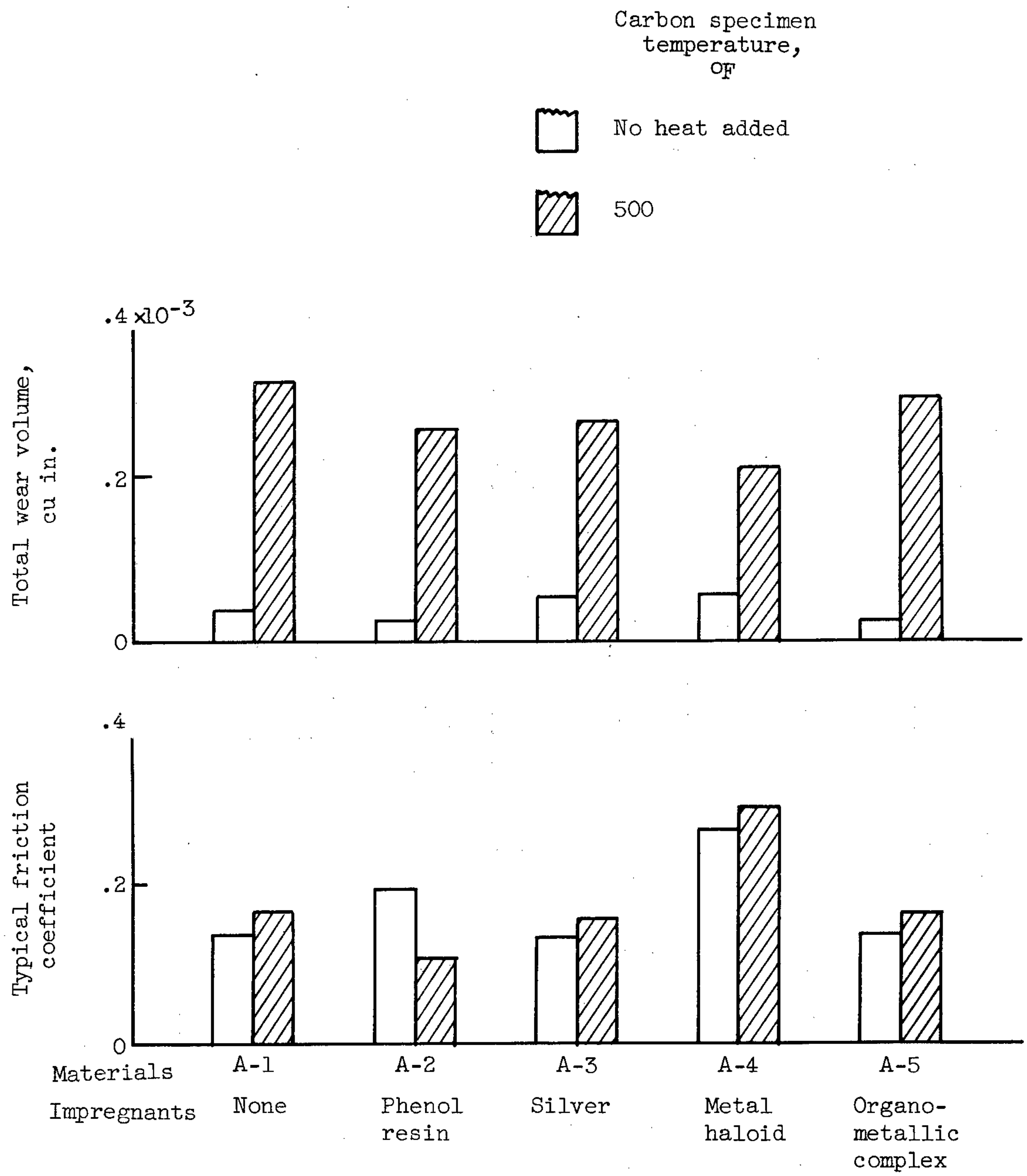


Figure 9. - Wear and friction of typical carbon seal materials with various types of impregnation sliding against 347 stainless steel. Load, 1000 grams; surface speed, 10,000 feet per minute; duration, 1 hour; hemispherical (3/16 in. rad.) specimen on superfinished (< 4 rms) disk.

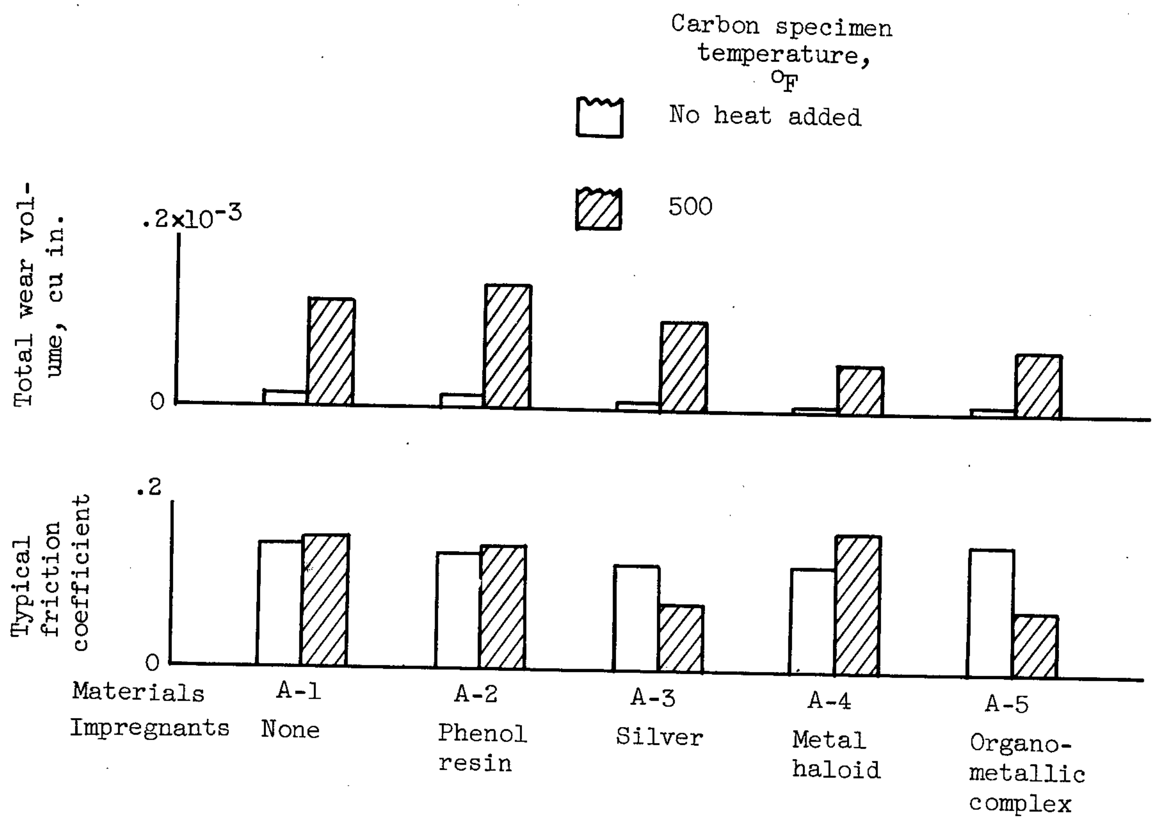


Figure 10. - Wear and friction of typical carbon seal materials with various types of impregnation sliding against chromium-plated steel. Load, 1000 grams; surface speed, 10,000 feet per minute; duration, 1 hour; hemispherical (3/16 in. rad.) specimen on superfinished (< 4 rms) disk.

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WEAR OF TYPICAL CARBON-BASE SLIDING SEAL MATERIALS AT TEMPERATURES TO 700° F. Robert L. Johnson, Max A. Swikert, and John M. Bailey. February 1956. 22p. diagrs., photos., tab. (NACA TN 3595)

Wear and friction studies were made with carbon-type seal materials sliding against tool steel, stainless steel, and chromium-plated steel at temperatures to 700° F and a sliding velocity of 10,000 feet per minute. Wear was several times greater at 500° F and above than with no heat added for all carbon materials. The mating material had more effect on wear and surface failure than did the use of various impregnants in the carbon. Chromium plate gave less wear than the other mating materials under all conditions of the experiment.

Copies obtainable from NACA, Washington

1. Friction and Lubrication - Surface Conditions (3.8.1.3)
2. Contact Surfaces, Sliding (3.8.2)
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